26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14 - 18 June 1999 ECA Vol.23J (1999) 473 - 476

Studies of Magnetic Reconnection, Helicity Injection, and Current Profile Control in the HIST Spherical Torus Experiment

M. Nagata, K. Goto, Y. Nasada, N. Yagi, N. Yuasa,
N. Fukumoto and T. Uyama
Faculty of Engineering, Himeji Institute of Technology
Shosha, Himeji, Hyogo 671-2201, Japan

1. Introduction

The purposes of the Helicity Injected Spherical Torus (HIST) experiments are to study MHD relaxation mechanism related to the non-inductive current drive by coaxial helicity injection (CHI) or compact torus (CT) injection (CTI). Helicity injection physics is important and has broad interests in not only nuclear fusion plasmas but also space plasmas. The HIST device ($R = 0.30$ m, $a = 0.24$ m, $A = 1.25$, $B_t \leqq 0.2$ T) [1] is characterized by the device's ability to form spherical torus (ST) configurations from a spheromak to a high q tokamak. So far, the internal magnetic configurations and MHD activities of ST plasmas have been investigated in the tokamak/spheromak hybrid operation regime. In the spheromak case, the rotating $n=1$ helical kink distortion of the open flux along the geometrical axis is known to play an important role in the current drive process [2][3]. However, in the tokamak case [4], it is unclear how much of closed'flux can be created by helicity injection because it is difficult to investigate the details of the internal magnetic structure without internal magnetic measurements. Hence, the helicity current drive mechanism of ST has not yet been established. In this paper, we report that the intermittent generation of toroidal current could be explained by the periodic injection of plasmoids formed by magnetic reconnection around the gun muzzle, which is similar to the plasmoid generation process in magnetospheric substorms and solar flares [5].

2. Experimental device and measurements

The HIST device, shown in Fig. 1, cau generate a helicitydriven ST, namely a spherical tokamak and a gun-spheromak with a central conductor by utilizing the variation of TF coil current from 0 to maximally 300 kAturns. The outer bias solenoid coil produces the bias flux Ψ_{bias} of $\leqq$ 2.5 mWb that is measured around the gun muzzle. The spherical solid copper flux conserver (FC) is 1 m in diameter and 3 mm in thickness. The TF coil is normally operated to generate the toroidal field B_t of 0.15 T at the magnetic axis.

In order to examine time evolutions of the internal magnetic structures, we used two 2D magnetic probe arrays that are located in the entrance region close to the gun muzzle and in a poloidal plane (R-Z) of the main region in the FC. The contours of poloidal flux are obtained by calculating $2\pi\int RB_z dR$, where B_z is an axial component of the poloidal field. We used the 6 channels λ probe incorporating small size Rogowski loops and flux loops to measure toroidal current density and toroidal flux profiles on the midplane of the FC. Two Mach probes for plasma velocity measurement are located at both sides of the X-type neutral point

3. Experimental results

We reported before that the HIST plasma with the peak plasma current of $I_t \leq 150$ **kA** and the averaged electron density of $<n_e>=2\sim8\times10^{19}$ m^{-3} **was** successfully maintained by CHI. Figure 2 shows that the typical temporal evolution of the toroidal current densities J_t measured at each radial position on the **midplane** of the FC using the A probe. We notice that the toroidal current is driven at the magnetic axis **(R=0.3** m) during the helicity injection phase and also there exists current fluctuation having larger amplitude than those on both edges. Another interesting event is that the current density profile changes from a hollow **profile** around the time of peak current **(t=0.5** ms) just after formation process to a peaked one during the sustainment phase. The $J_{t.axis}$ at the magnetic axis consists of an intermittently fluctuating component and an increasing pedestal component. The drive mechanism of pedestal of toroidal current can be explained by the model of Ohmic heating (OH) transformer effect from the open flux winding around the central conductor **[6]. Electrostatic** helicity injection is responsible for the regularly fluctuating component of $J_{t.axis}$. We have studied the current drive mechanism related to this fluctuation

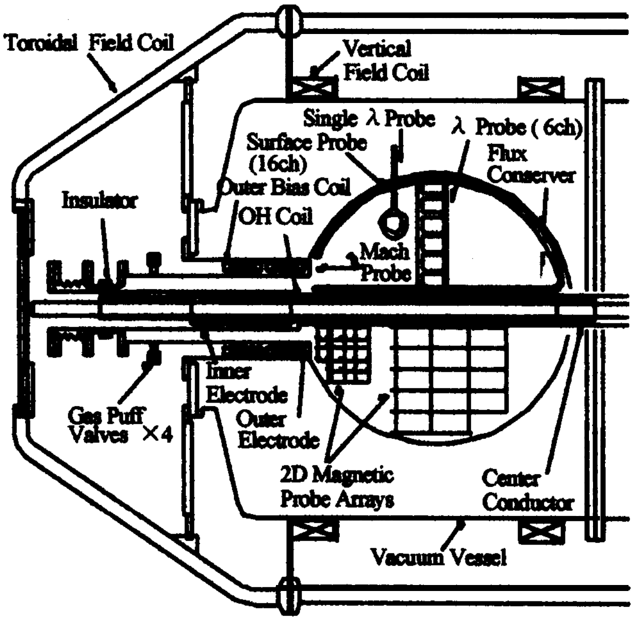

Fig.1 The schematic diagram of ***HIST***

Figure 3 shows the contours of the poloidal flux in the FC. We note that a doublet-type configuration is formed and two **annuli** (closed flux regions) merge each other. The closed flux surrounding the two **annuli** might be created by the OH transformer action, since it does not change during this relaxation cycle: The **annulus** in the left side is amplified during one cycle of *this* merging. We think that this amplification is caused by the **repeated** coalescence with a plasmoid periodically ejected from the coaxial plasma gun.

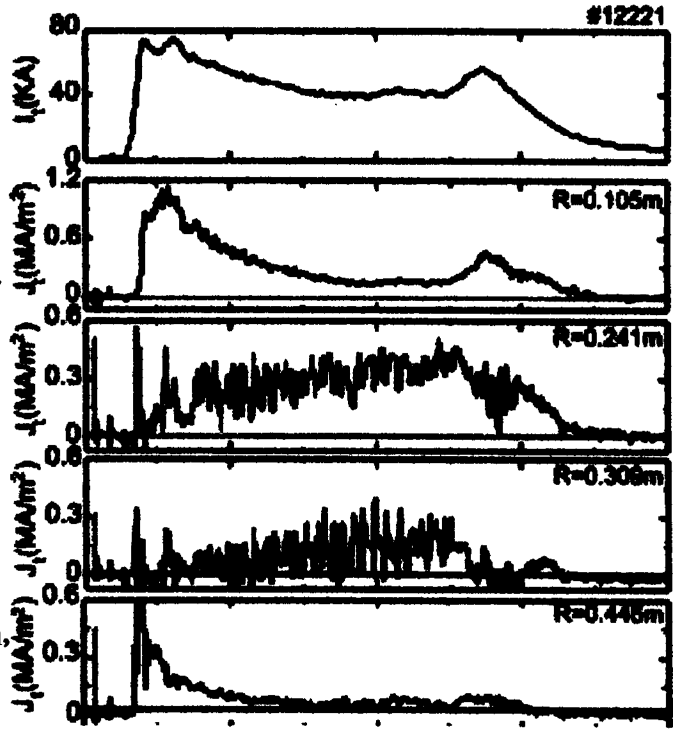

FIG.2 ***Time*** *evolution of the toroidal current density at each* ***radial*** *position.*

Figure 4 shows the time evolution of poloidal flux contours in the entrance region of the FC during the formation phase. We can see in this figure the temporal dynamics of plasmoid, i.e. formation and growing of plasmoid after magnetic reconnection. In Fig.4 (a) (b), we can see the swelling of the poloidal flux in the region of the gun muzzle (-0.45 m $<Z<-0.4$ m) since the electric field $\mathbf{E} = \mathbf{v} \times \mathbf{B}_{bias}$ produces the azimuthal current there, where $\mathbf{B}_{bias}$ is the bias field and v is the gun plasma flow accelerated by the $\mathbf{J}_g \times \mathbf{B}_t$ force, where $\mathbf{J}_g$ is the gun current and $\mathbf{B}_t$ is the toroidal flux. In the region of $Z > -0.37$ m, we can see a part of the closed flux surrounding the two **annuli.** Magnetic reconnection occurs drastically (Fig.4 (c) and (d)). A small plasmoid formed after the onset of reconnection glows to a large-scale as shown in Fig. 4 (e), (f) and (g). The magnetic energy and mass stored initially in the gun muzzle region release and transfer to the plasmoid through the reconnection. Then a large-scale plasmoid propagates toward the two **annuli** in the confinement region. The toroidal current increases during this propagation.

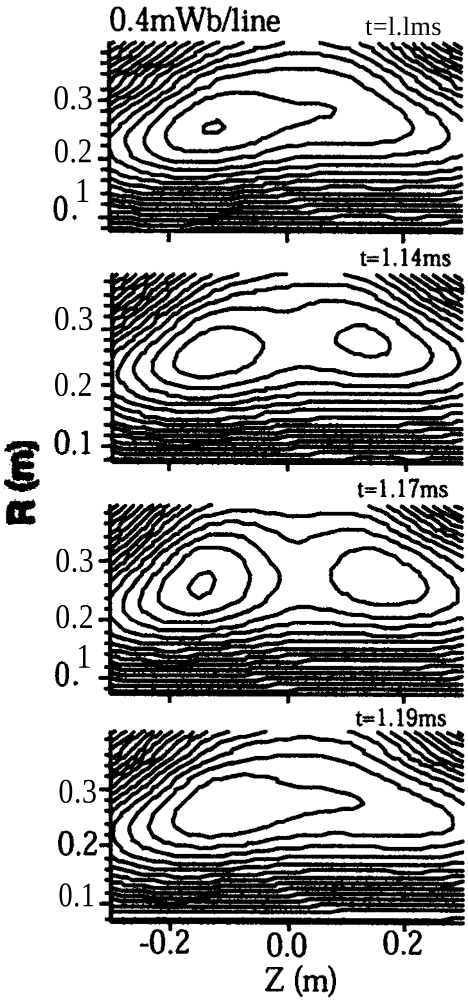

Fig.3 The contours of the poloidal flux in the confinement region at different times.

4. Summary and discussions

We propose that the periodic generation behavior of toroidal current in the core region is responsible to the repeated injection of plasmoid formed by the magnetic reconnection in the entrance region of the FC. The most important question is whether the repeated merging process can maintain the toroidal currents of ST plasmas. Flux surfaces which reconnect must have the same value of closed poloidal flux Ψ. If $\Psi_1 > \Psi_2$, then the value of poloidal flux Ψ_f after merging is Ψ_1, where subscript f corresponds to the final ST configuration, and the subscripts 1 and 2 correspond to the plasmoid and the initial ST plasma respectively. We can achieve the sustainment of poloidal flux by injecting a plasmoid having Ψ_1 when Ψ_2 decays less than Ψ_1 due to a plasma resistivity. When poloidal flux surfaces reconnect, the enclosed paramagnetic toroidal fluxes Φ_1, Φ_2 produced by the poloidal currents add, that is, $\Phi_f = \Phi_1 + \Phi_2$. In the spheromak case, this configuration after the reconnection is unstable, so the flux conversion from Φ_f to Ψ_f occurs which results in that Ψ_f is amplified above Ψ_1. In the high q tokamak case, it is hardly for the flux conversion to occur, because Φ_f becomes smaller as compared to the external toroidal flux (low paramagnetism). This means that helicity injection becomes less effective for generation of closed flux as the configuration approaches a spherical tokamak from a spheromak. This characteristic agrees with the experimental result from the measurement of the ratio M_Ψ of closed flux to total flux as a function of the TF coil current [6].

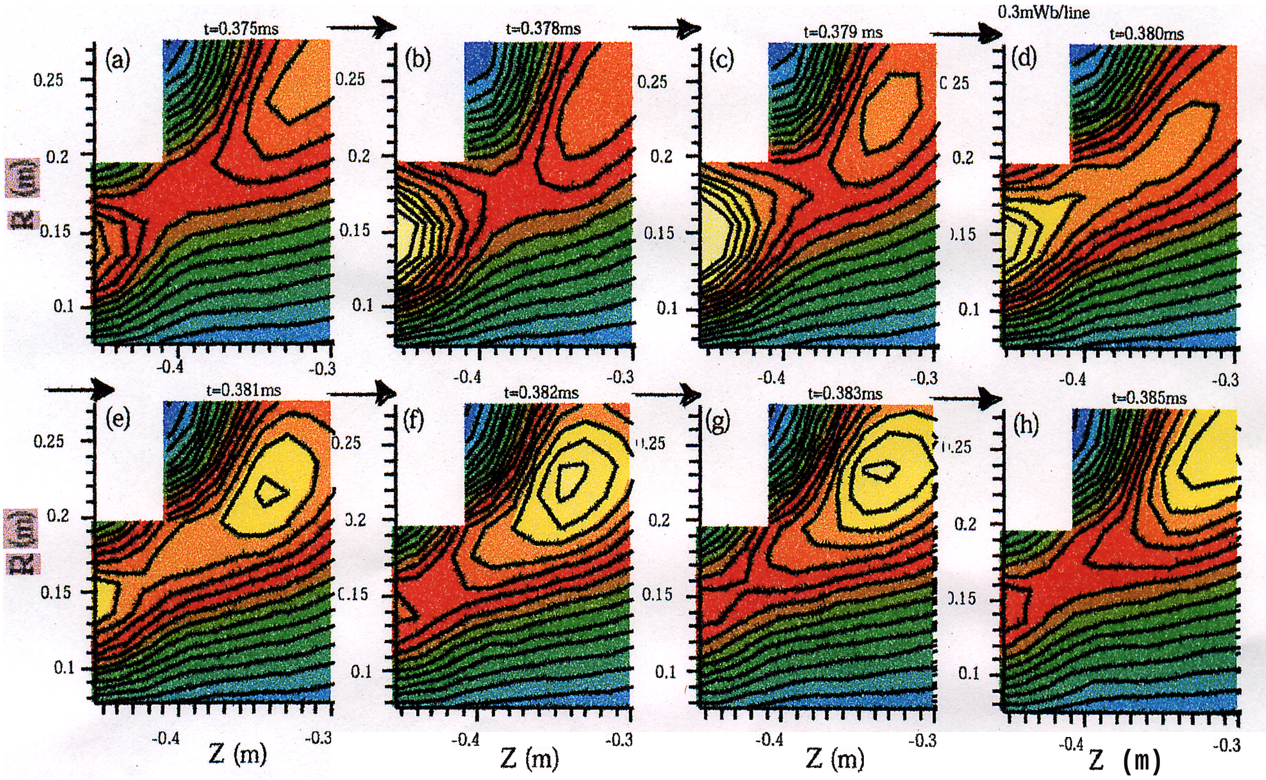

Fig.4 The temporal dynamics of plasmoids formed by the magnetic reconnection around the plasma gun muzzle.

Acknowledgments

The authors are grateful to P.K. Browning for many valuable comments. This work was partially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture of Japan.

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